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HARDI: A HIGH ANGULAR RESOLUTION DEPLOYABLE INTERFEROMETER FOR SPACE

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Abstract

We describe here a proposed orbiting interferometer covering the UV, visible, and near-IR spectral ranges. With a 6-m baseline and a collecting area equivalent to about a 1.4 m diameter full aperture, this instrument will offer significant improvements in resolution over the Hubble Space Telescope, and complement the new generation of ground-based interferometers with much better limiting magnitude and spectral coverage. On the other hand, it has been designed as a considerably less ambitious project (one launch) than other current proposals. We believe that this concept is feasible given current technological capabilities, yet would serve to prove the concepts necessary for the much larger systems that must eventually be flown.

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The interferometer is of the Fizeau type. It therefore has a much larger field (for guiding) better UV throughout (only 4 surfaces) than phased arrays. Optimize aperture configurations and ideas for the cophasing and coalignment system are presented. The interferometer would be placed in a geosynchronous or sunsynchronous orbit to minimize thermal and mechanical disturbances and to maximize observing efficiency.

Introduction

Observational optical astronomy is always scientifically driven to develop telescopes with fainter limiting magnitudes and higher resolution. However, it is clear that these two goals cannot be pursued simultaneously anymore. Larger ground-based telescopes have much greater collecting area but provide little improvements in resolution unless extremely demanding techniques are used. Space-based telescopes of traditional configuration such as the Hubble Space Telescope (HST) give great improvement in resolution (being diffraction limited), and a consequent improvement in limiting magnitude, but further improvements are limited by launch constraints. It is probably going to be impossible to launch a filled aperture telescope that gives an order of magnitude improvement in resolution over HST for the foreseeable future.

To achieve still higher resolution, interferometers are the answer. On the ground, baselines can be very large, but the atmosphere restricts integration time and therefore limits magnitude. A space-based interferometer, on the other hand, is not limited by integration time and thus could reach much fainter objects. Furthermore, a space interferometer, although likely to be limited in baseline initially, gets improved resolution from operation in the UV. (Near the Lyman continuum, a space interferometer will have about 4 times the resolution obtained from the ground in the U band with the same baseline.)

Many concepts for space-based interferometers have been proposed, but they are generally of major proportions, with baselines of 15 m or more that will require extensive technological development. We believe that the technical feasibility of space interferometry must be demonstrated before projects of this magnitude can be initiated. A smaller interferometer with a baseline on the order of 6 m would be less ambitious than the current generation of proposals and might consequently somewhat limit the science on which they are based. On the other hand, it would be much lower in cost, risk, and development time, and would serve as a stepping stone to the larger projects. The validation in space of enabling technologies in areas such as deployment, active optics, laser metrology, vibration suppression, high accuracy guiding, and pointing, would

be a major technological spinoff from such a project. Such validation is essential if the larger proposed projects are to be demonstrably feasible.

As shown in figure 1, even an interferometer of such a moderate size would offer important advances over both HST and ground-based interferometers, especially if it can be operated in the UV. For example, this would allow bright quasars, Seyfert galaxies, or stellar chromospheres at Lyman alpha to be imaged at several times the resolution of HST. For several scientific areas, the resolution of HST is just marginally inadequate (e.g., imaging the narrow emission line region in a variety of QSOs). Clearly, also, it will often be necessary to pursue the study of discoveries made with HST and the new large ground-based facilities at higher resolution.

We present here a first attempt at defining the main characteristics of an instrument corresponding to this rationale. We call this instrument "HARDI", for High Angular Resolution Deployable Interferometer. We also describe the various configurations and technological options that we plan to examine in detail as part of our ongoing preliminary study of the instrument.

Aperture Configuration

The optimal aperture configuration of an interferometer depends on a number of factors such as scientific goals, complexity of the observed objects, synthesized points spread function, deconvolution, speckle or phase closure techniques, and practical constraints. To determine the best configuration for our proposed instrument and scientific applications, we plan to do a comparative study of three typical configurations. The three aperture configurations, labelled Type I, II, and III have an outer diameter of 6 m and are very diluted with less than 6 percent filling factor.

Type I is composed of six 40-cm-diameter mirrors on six arms and a 1-m-diameter mirror on axis (5.4 percent fill factor). The aperture configuration is highly redundant with the intention of supplying a high signal-to-noise ratio (SNR) ^{1,2}.

Type II is a pupil function proposed by Cornwell³. It contains nine 40-cm-diameter mirrors arranged on a circle with a 2.8 m radius (4 percent fill factor). Its advantage is excellent instantaneous UV plane coverage which could have applications in the observation of ephemeral phenomena or microvariabilities.

Type III offers complete coverage of the UV plane by aperture synthesis. It is composed of six 60-cm mirrors (6 percent fill factor) arranged in such a fashion as to lead to a quasi uniform uv plane coverage when the entire telescope is rotated half a turn around its optical axis.

Type III has not been described elsewhere to our knowledge. In it, the mirror locations are such that the density of baselines increases roughly linearly with the separation. The idea is that the object spectrum for any system with unresolved bright components is close to flat. Therefore, one wants approximately equal coverage of the UV plane out to the diffraction limit to get the same SNR at each frequency. As longer baselines sweep a greater area when rotated, there needs to be more of them to give equal coverage.

A number of optimal Type III configurations were obtained for various numbers of subapertures and different subaperture sizes using the Monte Carlo method with more than 10,000 trials each. The subapertures were constrained to lie at equal distances from the optical axis, so that they can be fabricated by replication. Each subaperture was divided in 10x10-cm elements and the moduli of the elementary baselines were binned in 10-cm intervals. The optimization criteria was to minimize the rms of the spread of the modulus distribution with respect to the ideal function. We have selected a configuration with six 60-cm-diameter mirrors as being a good compromise between the number and size of subapertures.

Figure 2 shows the three configurations described above together with their corresponding UV plane coverage and point spread function in the image plane. We are planning to conduct computer simulations and laboratory experiments to evaluate these configurations as a function of the type of object to be resolved and the point spread function deconvolution algorithm.

Optical Design

Interferometers used in optical astronomy are generally of the Michelson type. This design suffers from a lack of field⁴ and poor throughput especially in the UV due to the large number of relay mirrors required. Our proposed instrument is of the thinned aperture or Fizeau type (figure 3). This interferometer configuration uses a smaller number of reflecting surfaces and offers a sufficient field of view to permit guiding using offaxis "bright" stars.

The final numerical aperture of the system is determined by the necessity to match the angular resolution of the system to the detector's pixel size. Using the Nyquist criterion, the final numerical aperture of the system must be $F/D = 2p/\lambda$, where F is final focal length of the system, D the overall aperture diameter, p the pixel size and λ the operating wavelength. Table 1 gives the minimum numerical aperture of the system as a function of the wavelength for current typical pixel sizes.

Table I

Wavelength (μm)	Resolution (milli-arcsec)	Detector pixel size (μm)	F/ratio for optimal match
1.0	42	50	100
0.6	25	15	50
0.24	10	15	125
0.12	5	15	250

Since a fast primary surface is essential to minimize the overall length of the telescope, obtaining such slow beams directly would lead to an impractical Cassegrain magnification. This is exemplified by figure 4 which shows the influence of the Cassegrain numerical aperture and that of the primary surface on the major optical parameters of the system. The tradeoffs are complex and will require an indepth study, but for the purpose of our conceptual study an $f/1.2$ primary and $f/12$ Cassegrain appeared to be reasonable combination. Optical relays will be used for reimaging onto the three detectors (UV, visible, and near-IR) with the appropriate scale. These relays should be coated to minimize reflecting losses in each of the wavelength bands.

The Cassegrain combination will be of the Ritchey-Chretien design to produce a large enough field of view. A total field of at least 10 arcmin in diameter is required to give a good probability of finding a pitch-yaw guide star in the 14th magnitude range. We would expect roll control to be achieved using fixed head star trackers. As in the case of the science field, reimaging will be required to produce a proper scale.

Cophasing and coaligning system. In view of the very tight tolerances on the respective position of the optical elements and the focal plane and the lack of external shielding, one cannot

rely on the dimensional stability of the structure, either passively (with insulation), or actively (with structural heaters). An active system is required to "freeze" the image during the exposures.

Our proposed active optics systems is composed of actuators on the primary mirrors and the secondary mirror served to a laser metrology system controlling the internal optical path lengths. This metrology system, using a Dyson⁵ interferometer, is described schematically in figure 5. The active optics system is bootstrapped by observing a bright star in the focal plane and coaligning and cophasing each primary aperture in successive pairs. Each primary would be depointable to remove its contribution from the focal plane. This is desirable to allow for failures on orbit in any event. The metrology system is then activated to "lock-in" the optical pathlengths between the various optical elements and the focal plane.

In addition to serve to cophase the interferometer, the active optics system will also be integrated in the pointing control system of the spacecraft. The pointing system will be composed of two layers. A traditional spacecraft attitude control based on gyroscopes and star trackers will be used for slewing and coarse pointing. The fine pointing (guiding) will be done by using the active optics system to steer the optical beam based on the information supplied by a guide star in the field.

Spacecraft General Design and Orbit

As shown in figure 6, the supporting structure is composed of a central tower and six articulated arms. These arms are braced with telescopic members which extend for deployment and confer axial rigidity to the structure. Once open, the moments of inertia around the three axes are nearly equal, thus minimizing the attitude control requirements.

The entire interferometer assembly is protected from the sun by a sunshade located on the rear of the spacecraft. There are no side baffles. This leads to a considerable simplification of the spacecraft structure, but the price to pay is that the pointing has to be limited to about 45 degrees from the antisun direction. The solar arrays are attached to the sunshade to avoid the low frequency excitations that a steerable system would create.

The entire telescope structure and optics will be passively cooled by radiation against the sky to allow near IR observations. Preliminary calculations indicate that a temperature on the order of 100 K may be attainable.

As for the orbit, we are conducting an indepth study to determine which of the possible Earth orbits would be the most favorable for the proposed instrument. Factors such as thermal and mechanical disturbances, sky coverage, radiation level, observing efficiency, baffling, and communication are being considered. So far the main contenders appear to be the 6-pm sunsynchronous and geosynchronous orbits which offer significant advantages over low Earth orbit.

The overall mass of the spacecraft is estimated at 3 tons, which is compatible with the payload capacity to sunsynchronous or geosynchronous orbit of medium-sized launchers such as Ariane 4.

Conclusion

We have outlined here our approach to going beyond the resolution of HST. It seems to us that a space interferometer is eventually going to be a necessary next step. Even with a modest baseline the scientific drivers are enormous. The concept we are developing forms the basis for a cost effective first attempt in this direction.

References

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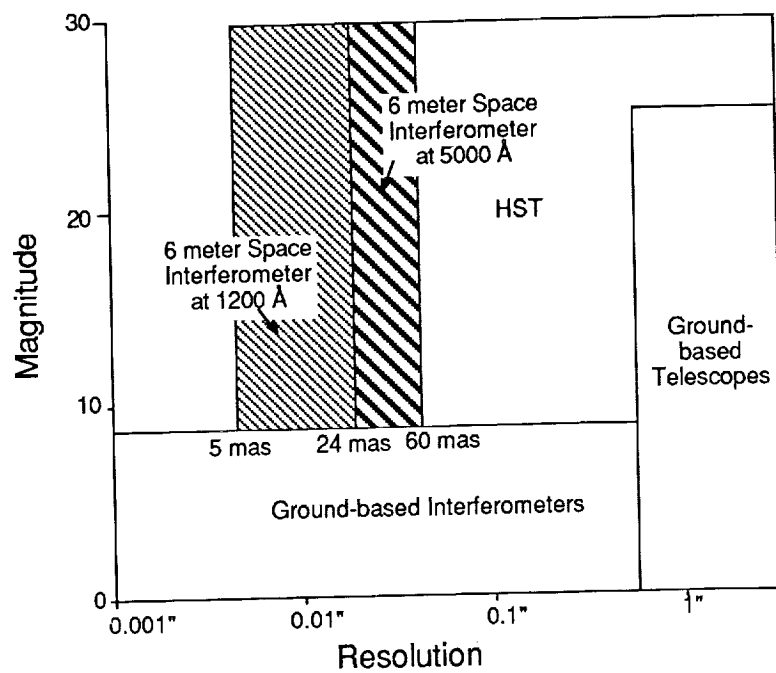


Figure 1: Domain of the proposed interferometer (hatched area) compared to that of existing or proposed instruments.

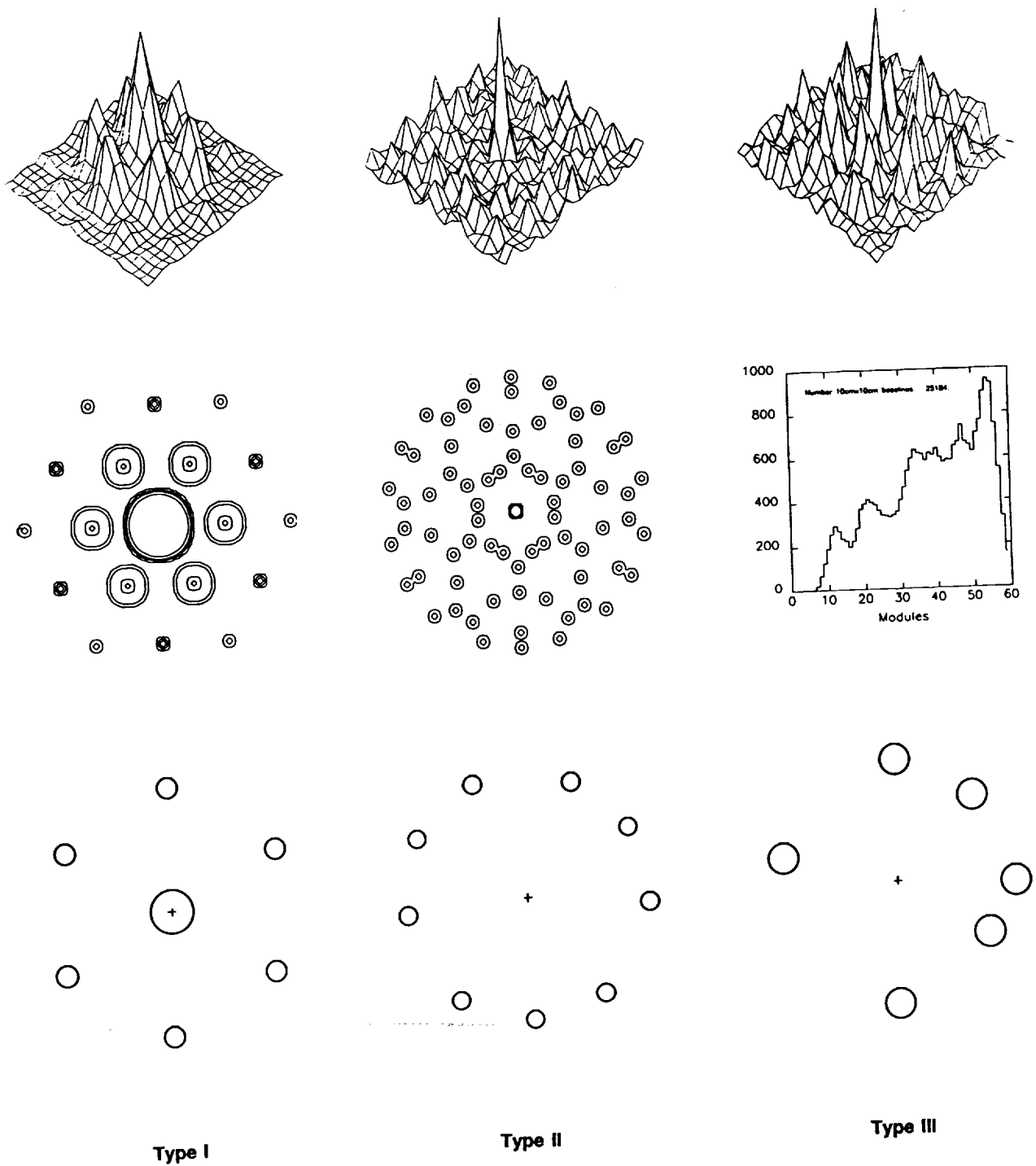


Figure 2: The three aperture configurations under study (bottom) shown with their UV plane coverage (middle) and the point spread function (top). For Type III which is rotated around its axis during observations, the histogram of the baseline modules is shown instead of the two-dimensional UV plane.

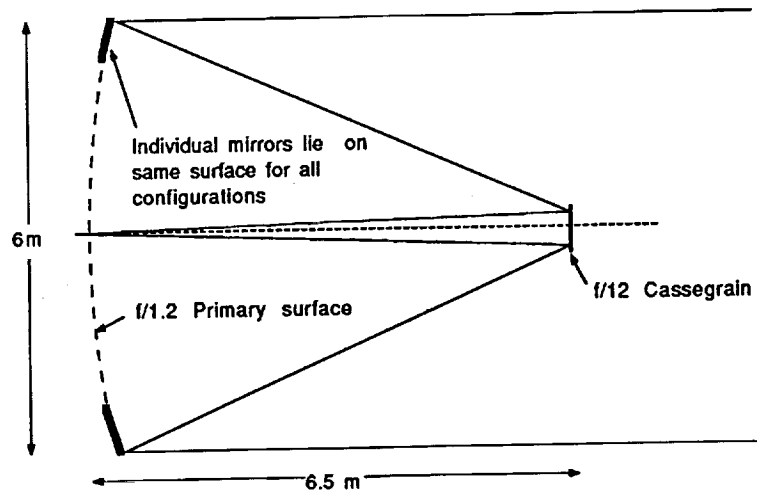


Figure 3: Schematic optical diagram of the proposed interferometer. The Fizeau configuration is preferred over the Michelson type because of its larger field and small number of reflecting surfaces.

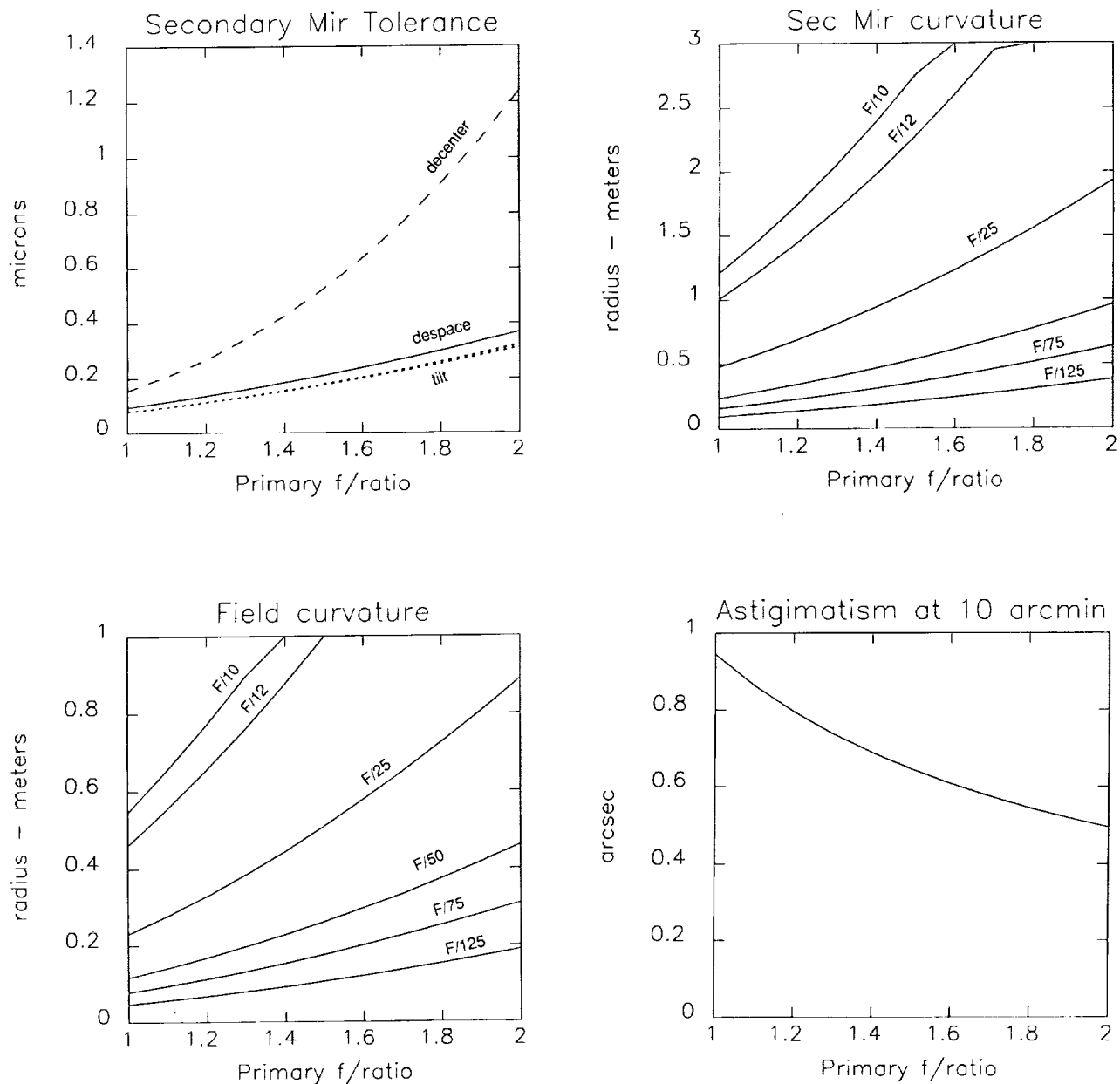


Figure 4: Effect of the primary mirror surface and final beam numerical aperture on the secondary mirror positioning tolerances, secondary mirror curvature, field curvature, and astigmatism. Only the secondary mirror curvature and field curvature are dependent on the final beam numerical aperture, the secondary mirror position tolerance and astigmatism are not, at least to the first order. All effects are shown for 1200\AA and assuming a Ritchey-Chretien combination. The value for the secondary mirror tilt tolerance is given in displacement at the edge of the mirror.

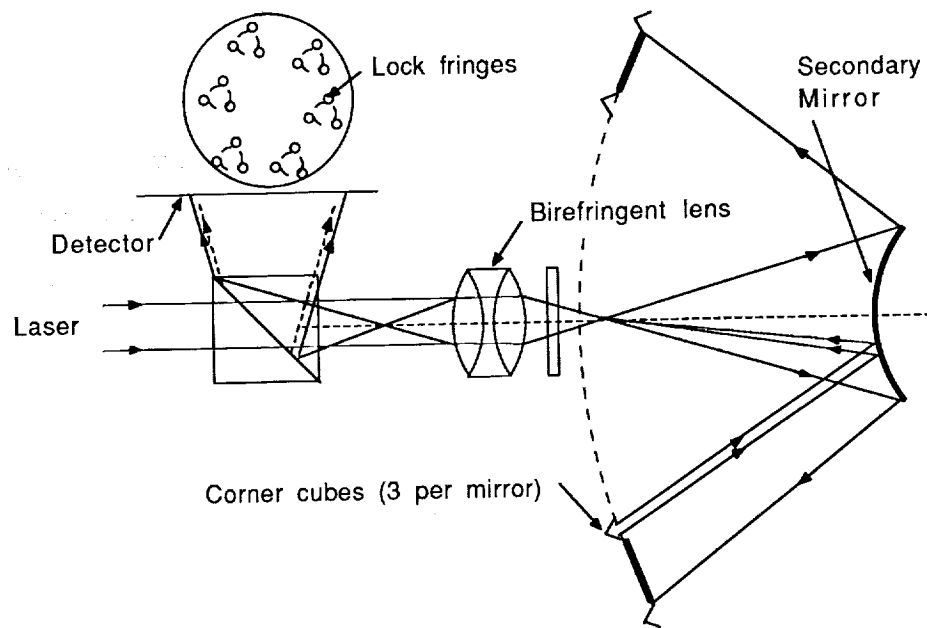


Figure 5: Coaligning and cophasing system. A Dyson interferometer setup is used to maintain the optical path lengths in the system using retroreflectors mounted at the periphery of the primary mirrors.

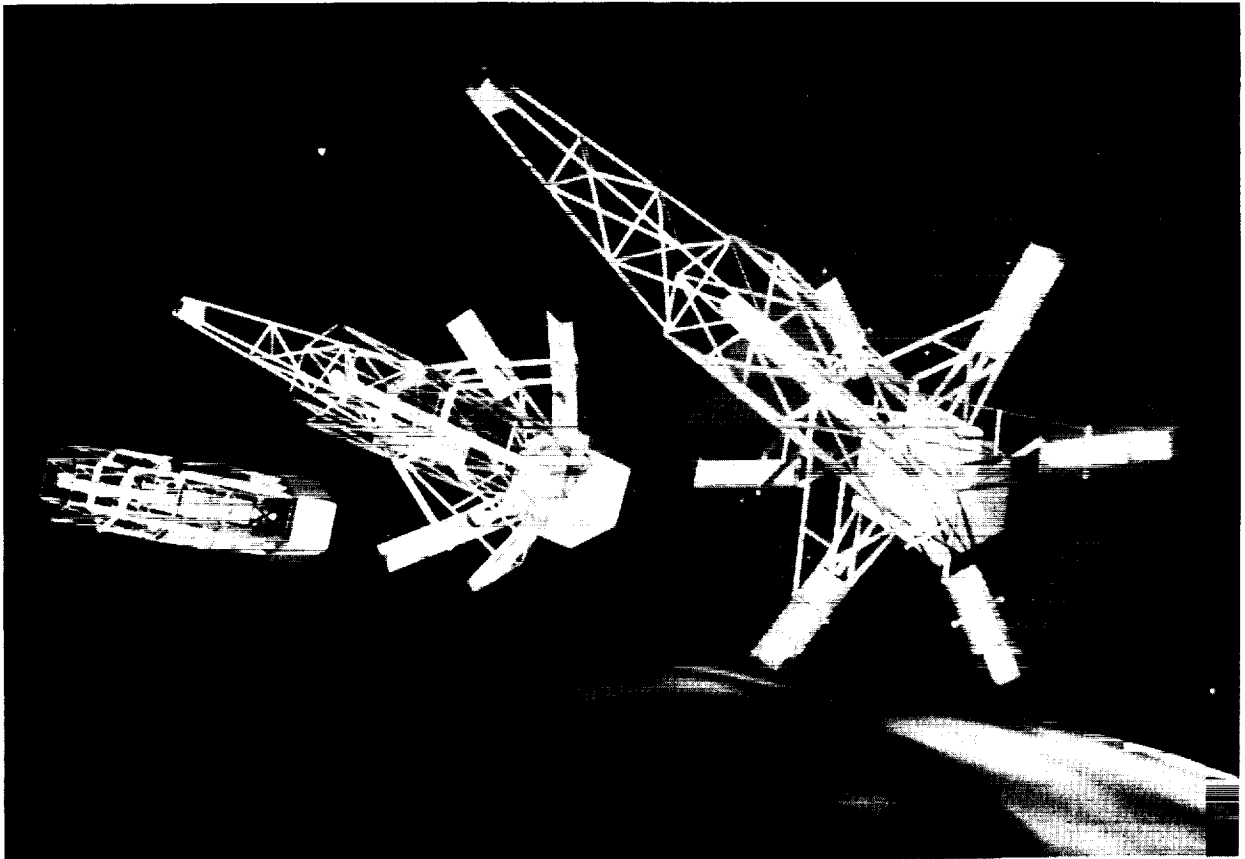


Figure 6: Artist's view of the proposed interferometer during deployment.